Renewable and Sustainable Energy Reviews 16 (2012) 5121–5130

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The potential of solar heat for industrial processes in Germany

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ARTICLE INFO

Article history:
Received 25 January 2012
Received in revised form
17 April 2012
Accepted 18 April 2012
Available online 27 June 2012

Keywords:
Solar heat for industrial processes
Potential
Suitable sectors and processes
Germany

ABSTRACT

Industry represents a very promising application area for solar thermal technology, since it accounts for 27% of the total final energy consumption in Germany and uses 74% of its energy consumption as thermal energy. In order to develop this application area, it is necessary to know which industrial sectors have the highest potential and which processes within these sectors are most suitable for the integration of solar heat. For this paper the industrial heat consumption in Germany was analyzed, which leads to the selection of the most promising sectors within industry. Furthermore, the quantitative potential for Germany in total and for 11 selected sectors, that were identified to be most promising for the use of solar heat, was calculated. These are Chemicals, Food and beverages, Motor vehicles, Paper, Fabricated metal, Machinery and equipment, Rubber and plastic, Electrical equipment, Textiles, Printing and Wood. These sectors are analyzed to identify suitable processes for the integration of solar heat. In total the theoretical potential of solar heat for industrial processes below 300 °C in Germany accounts for 134 TWh per year, the technical potential being 16 TWh per year or 3.4% of the overall industrial heat demand. This is the highest share of the European potential of 72 TWh per year. The results of this study facilitate the prioritized application of solar thermal energy in industrial sectors and processes for Germany and other countries.

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1. Introduction

Since 56% of the total final energy consumption in Germany is for thermal uses, renewable heating technologies are especially important to reduce greenhouse gas emissions. Process heat has, besides space heating (55%) and domestic hot water (8%), a major share (37%) of this heat consumption. Within the industrial sector, even 74% of the final energy consumption is needed to provide mainly process heat, but also space heating and hot water [1]. In 2010, renewable heating technologies provide a share of 9.5% of the German heat supply, whereas biomass accounts for 90% and only 4% is provided by solar thermal systems. Because the potential of biomass is limited, the further use of solar and geothermal heat plays an important role for the reduction of greenhouse gas emissions and independence of fossil fuels [2].

Today, solar thermal systems are nearly exclusively used for providing hot water, space heating and heating of swimming

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http://dx.doi.org/10.1016/j.rser.2012.04.032

pools. The conditions for the use of solar thermal are favorable in the industrial sector, because in many cases the load is constant over the year and existing storages might be used. However, only a few systems were installed in industrial companies in Germany and worldwide, so solar thermal systems in industry have a negligible share of 0.02% compared to the installed capacity worldwide [3].

Potential studies for the use of solar heat for industrial processes (SHIP) were carried out in the past for different countries or regions. A comprehensive study for Spain and Portugal identifies several sectors and processes to be suitable for the use of solar heat [4]. A similar study was performed for Austria [5]. Further potential studies for Victoria (Australia) [6], Italy [3], the Netherlands [7], Sweden [8], and Cyprus [9], partly support the identified sectors, but only identify a few additional ones. Aidonis et al. [10] performed a study for Greece, Wallonia (Belgium) and few industrial sectors in Germany.

So far, no comprehensive potential study was done for Germany. Furthermore, no detailed analysis of the industrial heat demand below 300 °C exists.

Therefore, this paper tries to bridge the knowledge gap regarding the distribution of temperature levels of the industrial heat demand, which is crucial for the application of solar thermal systems in industry. Further, the potential contribution of solar heat for a sustainable heat supply in industry has to be quantified. Finally, the suitable industrial sectors and processes have to be identified to facilitate the prioritized application of solar heat in industry.

For this study the industrial heat demand in Germany was analyzed and different sources were combined to determine the shares of temperature levels below 300 °C and the quantitative potential of solar heat for industrial processes. The most promising industrial sectors and processes for the application of solar process heat were selected based on their heat demand below 300 °C and waste heat potential. This selection was verified with the results of prior studies. In Section 2, methodological approaches for potential studies in the field of solar process heat are introduced, using two comprehensive studies as examples. Further, the approach for this study is illustrated. In Section 3, the industrial heat demand in Germany is analyzed, and the shares of the relevant temperature levels are calculated. Section 4 explains the determination of the potential for solar heat in industrial processes in and a theoretical as well as a technical potential is calculated. Finally, these suitable industrial sectors are analyzed and suitable processes for the integration of solar heat are identified in Section 5.

2. Methodological approach

Prior potential studies in the field of solar heat for industrial processes differ significantly regarding their approach to select suitable industrial sectors and processes and their way to determine a quantitative potential. In some studies the potential is determined based on the energy and heat demand of industrial sectors, one uses the available roof area and others calculate the potential on the basis of case studies of selected industrial companies. For the choice of a suitable approach for this study the ones of prior studies were analyzed and compared. Generally, it can be distinguished between a top-down and a bottom-up approach.

For the top-down approach, data, e.g., distribution of heat demand or available roof area, for the whole industry is analyzed to select suitable sectors and calculate a quantitative potential. This approach is followed in the comprehensive potential study for Austria in 2004 [5]. In a first step, the energy demand of the industry in Austria is analyzed and the low (<100 °C) and medium temperature (<250 °C) heat demand is calculated by adding the demand for space heating and steam generation for all industrial sectors. Hot water consumption is not mentioned, which only leads to a minor uncertainty because its share in industry is very low. At first, suitable sectors are selected to determine a theoretical potential. Therefore, sectors with a low heat demand or high waste heat potential are excluded. The sectors of Chemicals, Food and beverages, Rubber and plastics, Textiles and Prefabricated concrete components are selected. Further, the processes of washing, cleaning and surface treatment of metals are mentioned as suitable for the use of solar heat. The low and medium temperature heat demand of the mentioned sectors and processes is defined as the theoretical potential. This theoretical potential is divided in a short-term (<100 °C) and a mid-term (<250 °C) potential because at the time of the study collector technology for process heat generation at temperatures above 100 °C was neither technically mature nor available on the market. The technical potential was calculated by deducting the renewable share of 15% of the heat supply and further 60% due to possible efficiency measures and restrictions regarding economic feasibility. In addition an average solar fraction of 40% for process heat applications and 20% for space heating is assumed by the authors. The figures for efficiency measures and solar fraction are not explained in detail.

For a bottom-up approach, selected industrial companies are analyzed and the results are used to determine suitable sectors and a quantitative potential using statistics of the overall industrial heat demand or number and size of companies. This approach is followed in the potential study for Spain and Portugal [4]. The aim of this study was to determine the potential for solar heat at low (<60 °C) and medium (60 to 160 °C) temperatures. In a first step nearly 1700 enterprises were contacted by mail or called. In total 59 answers were received and finally case studies were performed in 34 industrial enterprises in Spain and Portugal. More than half of the enterprises belong to the sector Food and beverages and few case studies were done in Paper (4), Textiles (6), Leather (2), and one each in Cork and Automobile. The temperature distribution of the heat demand of each sector was determined on the basis of these case studies and the share of low and medium temperature heat demand of the whole sector was calculated. A theoretical potential is not clearly defined. The technical potential was determined by estimating the available roof area for each enterprise analyzed, which was the limiting figure in most cases, and assuming a maximum solar fraction of 60%.

Comparing the two approaches, the advantage of a top-down approach is a coherent distribution of the industrial heat demand, which is the necessary basis to calculate a theoretical potential. This is, however, only true, if the used data can be verified. The calculation of the distribution of the industrial heat demand with a bottom-up approach incorporates, as the above mentioned example shows, a high uncertainty unless a large number of companies are studied. In order to determine the temperature distribution and a theoretical potential, the top-down approach seems to be the better choice as the feedback to questionnaires is typically very low. Figures for restrictions as e.g., limited roof area or possible priory efficiency measures as well as a solar fraction are necessary in order to calculate a technical potential. In case of a top-down approach one relies on assumptions for these figures, as the above example shows. Using a bottom-up approach the figures can be estimated with a much better certainty, again only if the number of enterprises studied is high enough. Nevertheless, the results of case studies have to be verified with literature. As the execution of a large number case studies need high resources, this could be replaced by studying case studies and built examples from literature, possibly combined with a few additional case studies.

The choice for one of the described approaches also depends on the availability of data regarding the overall industrial heat demand and its temperature distribution.

As comprehensive data is available for Germany from studies for technologies such as combined heat and power and heat pumps, a top-down approach was chosen for this study.

The first step was the analysis of the industrial heat demand and the calculation of the shares of the relevant temperature levels, as explained in detail in Section 3. Afterwards the theoretical potential was calculated. This was defined as the heat demand at temperatures below 300 °C of all industrial sectors except the ones with a high waste heat potential. Furthermore, the technical potential was determined by considering restricted roof area and possible efficiency measures, as well as an average solar fraction, as described in Section 4. A reduction for the existing renewable share was not considered as this is incorporated in the solar fraction and biomass can also be used to provide higher temperatures or to cover the heat demand in winter. By assuming an average energy yield per square meter of collector, the necessary collector area could be calculated, which also determines the market size. Furthermore, the most promising sectors were selected using their overall heat demand below 300 °C and waste heat potential as the two criteria. Finally, the selected sectors were analyzed to identify suitable processes for the use of solar heat.

3. Industrial heat demand in Germany

The final energy consumption in Germany was 2414 TWh in 2009, the industrial sector's share was 641 TWh, representing 27%. The heat demand, including process heat, space heating, and DHW, is of high importance as it accounted for 74% of final energy consumption in industry, as shown in Fig. 1 [1].

Today, the heat supply is mainly provided by fossil fuels. The fuel with the largest share is natural gas with 47% followed by coal with 21%. Oil and electricity both have a share of 8%, district heat 7% and renewables 5%. Other fuels have a share of 4% [1]. In order to determine the theoretical potential for solar heat in industrial processes, a thorough analysis of the industrial heat demand and its temperature levels is necessary. Table 1 shows the industrial heat demand in Germany for 2009 divided by temperature level.

This data was calculated by using employee-specific heat demand figures from [11], which have been determined by investigating about 150 representative energy consumers and about 90 typical buildings. As the number of analyzed companies and buildings is quite high, it can be assumed that employee-specific heat demand figures reasonably reliable. Further the numbers of employees for 2009 per sector from the German Federal Statistical Office were used [12]. To verify the calculated industrial heat demand the last line of Table 1 shows the aggregated values for hot water, space heating and process heat for 2009 from the official energy statistics of the German Federal Ministry of Economics and Technology [1].

The comparison with the calculated values shows a good accordance of figures for the total industrial heat demand with a deviation of only 1%. The values for process heat and space heating also accord well with the calculated values, only for hot water there is a deviation of 26%, which is, however, of minor importance for the overall heat demand. Three industrial sectors, Chemicals, Non-metallic mineral products and Basic metals, dominate the industrial heat demand in Germany, and had an aggregated share of nearly 75% of the industrial heat demand in 2009. Additional sectors with relevant shares are Food and beverages, Motor vehicles, Paper, Fabricated metal, and Maschinery and equipment. These five sectors have an aggregated share of nearly 20%. Regarding the temperature level, Table 1 shows that high temperatures above 500 °C had a large share of 65% of the

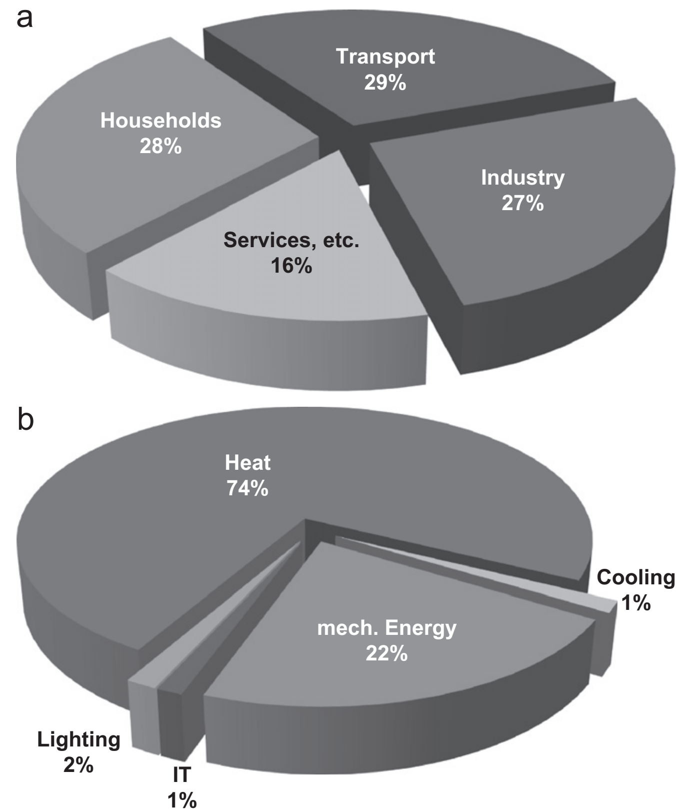

Fig. 1. Final energy consumption in Germany and distribution within industry in 2007 [1].

industrial heat demand. Processes with high temperatures are mainly found in heavy industries like Basic metals and Non-metallic mineral products. A share of 14% was consumed in the medium temperature range of 100 to 500 °C, 21% in the low temperature range which includes process heat at low temperatures, space heating and hot water. The sectors Chemicals and Food and beverages had by far the highest share in the low temperature range for process heat below 100 °C, space heating and hot water with 20% each. In order to determine the potential for the use of solar heat for industrial processes in Germany, the heat demand below 300 °C is especially important, as for the temperature ranges of 100 to 200 °C and 200 to 300 °C different advanced systems and components are necessary. Therefore, the temperature range from 100 to 500 °C was further divided. Fig. 2 shows a breakdown of the industrial heat demand by temperature level from 100 to 500 °C for Chemicals, Food and beverages, and an average of other sectors [13]. Hofer [13] determines the shares of the industrial heat demand differently for sectors with highly standardized production processes like e.g., Non-metallic mineral products and inhomogeneous sectors like e.g., Food and beverages. In case of standardized production processes, the energy demand and necessary temperature for every processes step is analyzed and the temperature distribution is calculated based on the production volume. For inhomogeneous sectors the overall energy and heat demand is taken from official statistics and case studies are performed to derive the temperature distribution of their heat demand.

As the classification of industrial sectors was different at the time of [13] it was not possible to derive a temperature distribution for all sectors. Therefore, only Food and beverages and Chemicals are displayed separately as they are most important, whereas for the other sectors an average is used. This incorporates an

Table 1
Breakdown of the industrial heat demand for the year 2009 [11], [12].

Industrial sector (NACE Rev.2 Code)	**HW**	**SH**	**Process heat [TWh]**				**Sum**	**Share*** (%)
			< 100 °C	**100–500 °C**	**500–1000 °C**	**> 1000 °C**		
Food products and beverages (10/11)	0.3	8.3	11.8	14.6	0	0	35.0	7.5
Tobacco products (12)	0.0	0.0	0.0	0.0	0	0	0.1	0.0
Textiles (13)	0.1	1.2	2.0	0	0	0	3.3	0.7
Wearing apparel (14)	0.0	0.1	0.2	0	0	0	0.3	0.1
Leather and related products (15)	0.0	0.1	0.2	0	0	0	0.3	0.1
Wood and wood products (16)	0.0	0.3	1.5	0.4	0	0	2.1	0.5
Paper and paper products (17)	0.1	2.4	2.7	9.9	0	0	15.1	3.2
Printing and reprod. of recorded media (18)	0.0	0.4	0.2	2.7	0	0	3.3	0.7
Chemicals and chemical products (20/21)	0.2	6.7	13.5	20.9	44.7	11.0	96.9	20.7
Rubber and plastic products (22)	0.1	1.6	0.9	3.5	0	0	6.1	1.3
Non-metallic mineral products (23)	0.1	3.5	1.2	1.8	26.9	55.8	89.3	19.0
Basic metals (24)	0.2	4.4	0.9	2.7	31.5	123.5	163.1	34.8
Fabricated metal products (25)	0.9	6.3	2.3	1.8	1.0	2.4	14.8	3.2
Computer, electronic, optical products (26)	0.1	0.9	0.3	0.2	0.1	0.3	2.0	0.4
Electrical equipment (27)	0.3	2.4	0.9	1.1	0.3	0.8	5.8	1.2
Machinery and equipment (28)	0.6	4.5	1.6	1.2	0.6	1.7	10.3	2.2
Motor vehicles and trailers (29)	1.0	7.3	2.7	2.0	1.0	2.8	16.8	3.6
Other transport equipment (30)	0.1	0.9	0.3	0.2	0.1	0.3	2.0	0.4
Furniture and other goods (31/32)	0.0	0.7	0.4	1.0	0.0	0.1	2.4	0.5
Sum	**4.2**	**52.0**	**43.6**	**64.2**	**106.2**	**198.7**	**468.9**	**100**
Share*	1%	11%	9%	14%	23%	42%	100%	–
Figure from [1]	5.7	49.4	418.6				473.7	–

* of the overall industrial heat demand; Mineral oil (19) not listed as demand is covered by own production; all numbers without unit in TWh; HW: hot water; SH: space heating.

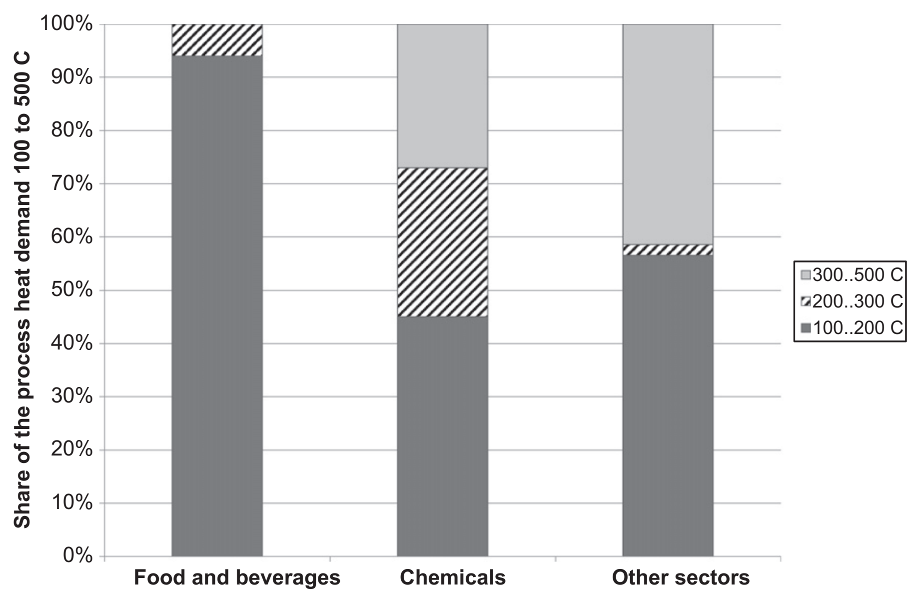

Fig. 2. Breakdown of the industrial process heat demand between 100 and 500 °C (own figure derived from [13]).

uncertainty for the temperature distribution. Nevertheless, Food and beverages and Chemicals have a share of 55% of the 100 to 500 °C temperature range as shown in Table 1. Further, the distribution for Paper, which has a share of 15% of the 100 to 500 °C temperature range, was verified within the analysis done for Section 5. Although this distribution is not completely correct for individual sectors as e.g., Printing, it seems acceptable to use the average distribution for other sectors. The distribution of Fig. 2 was used to calculate the distribution of temperatures within the 100 to 500 °C temperature range of Table 1. Table 2, which is sorted by the head demand below 300 °C, shows the detailed distribution. Twenty-one percent of the industrial heat demand is in the temperature range lower than 100 °C for process heat, space heating and hot water, which is very promising for the application of solar heat, as the efficiency of solar thermal systems declines with rising temperatures. Additional 8% are in the temperature range of 100 to 200 °C. The share of the industrial heat demand in the temperature range of 200 to 300 °C is reasonably smaller. The sectors of Chemicals and Food and beverages have by far the highest shares of the heat demand below 300 °C.

The majority of the heat demand in Germany is needed at temperatures above 500 °C with a share of 65%, of which 78% is used in Basic metals and Non-metallic mineral products. A possible uncertainty of this high temperature heat demand would change the presented shares. Assuming e.g., a negative 10% deviation in the heat demand over 500 °C of Basic metals and Non-metallic mineral products leads to a increased share of the overall low temperature (< 100 °C) heat demand from 21 to 22.4%.

Table 2
Breakdown of the industrial heat demand with detailed temperature distribution between 100 and 500 °C.

Industrial sector (NACE Rev.2 Code)	**HW**	**SH**	**Process heat [TW h]**					**Sum**	**Sum < 300 °C**
			< 100 °C	**100–200 °C**	**200–300 °C**	**300–500 °C**	**> 500 °C**		
Chemicals and chemical products (20/21)	0.2	6.7	13.5	9.5	5.9	5.5	55.7	96.9	35.7
Food products and beverages (10/11)	0.3	8.3	11.8	13.7	0.9	0.0	0.0	35.0	35.0
Motor vehicles and trailers (29)	1.0	7.3	2.7	1.1	0.0	0.8	3.7	16.8	12.2
Paper and paper products (17)	0.1	2.4	2.7	5.6	0.2	4.1	0.0	15.1	11.0
Fabricated metal products (25)	0.9	6.3	2.3	1.0	0.0	0.8	3.4	14.8	10.6
Machinery and equipment (28)	0.6	4.5	1.6	0.7	0.0	0.5	2.3	10.3	7.5
Basic metals (24)	0.2	4.4	0.9	1.5	0.1	1.1	154.9	163.1	7.0
Non-metallic mineral products (23)	0.1	3.5	1.2	1.0	0.0	0.7	82.7	89.3	5.9
Rubber and plastic products (22)	0.1	1.6	0.9	2.0	0.1	1.4	0.0	6.1	4.7
Electrical equipment (27)	0.3	2.4	0.9	0.6	0.0	0.5	1.1	5.8	4.3
Textiles (13)	0.1	1.2	2.0	0.0	0.0	0.0	0.0	3.3	3.3
Printing and reprod. of recorded media (18)	0.0	0.4	0.2	1.5	0.1	1.1	0.0	3.3	2.2
Wood and wood products (16)	0.0	0.3	1.5	0.2	0.0	0.2	0.0	2.1	2.0
Furniture and other goods (31/32)	0.0	0.7	0.4	0.6	0.0	0.4	0.2	2.4	1.8
Computer, electronic, optical products (26)	0.1	0.9	0.3	0.1	0.0	0.1	0.4	2.0	1.5
Other transport equipment (30)	0.1	0.9	0.3	0.1	0.0	0.1	0.4	2.0	1.4
Leather and related products (15)	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.3	0.3
Wearing apparel (14)	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.3	0.3
Tobacco products (12)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Sum	**4.2**	**52.0**	**43.6**	**39.3**	**7.5**	**17.4**	**304.9**	**468.9**	**146.6**
Share*	1%	11%	9%	8%	2%	4%	65%	100%	31%

* of the overall industrial heat demand; all numbers without unit in TWh; HW: hot water; SH: space heating.

In contrast to this temperature distribution, [14] states that a third of the industrial heat demand in Europe is at temperatures lower than 100 °C and nearly 60% at temperatures below 400 °C. These figures were determined by applying a temperature distribution for the German industry [15] to the energy balances of other countries [16]. An explanation for the deviation in temperature distribution might be the minor role of several industries with low temperature heat demand as e.g., Food and beverages, Textiles, Wearing apparel and Wood in Germany compared to the average of Europe [17].

Other references support the temperature distribution determined in this study [18] states that a comparably low heat demand exists for process temperatures between 200 and 800 °C in Germany and about one third of the heat demand is needed at temperatures below 200 °C. Lambauer [19] investigates the potential of heat pumps to provide heat up to 100 °C in the German industry. The industrial heat demand below 100 °C, which is defined as the technical potential, is calculated with 108 TWh for 2006. This result also supports the values of Table 2, where the heat demand below 100 °C sums up to 100 TWh, and according to [1] the energy demand in industry decreased by about 11% from 2006 to 2009.

4. Potential in Germany and Europe

The theoretical potential of solar heat for industrial processes in Germany was determined by adding the sum of process heat below 300 °C and the demand for space heating and hot water for all industrial sectors, except Basic metals and Non-metallic mineral products. These sectors were not considered as they have by far the highest waste heat potential. This leads to a theoretical potential of 134 TWh per year. In order to calculate the technical potential further restrictions were taken into account.

First of all, the heat demand in many industrial enterprises can easily be reduced by heat recovery measures, such as an economizer for the steam boiler or the use of waste heat from cooling and compressed air. Heat integration of several processes can further reduce the heat demand. In addition, a fraction of the required heat has to be supplied by electricity out of operational reasons. Finally, in many cases no sufficient space is available for the installation of solar thermal systems [4] and many roofs in industry are not capable of carrying additional static loads. In [5] it is assumed that a share of 60% of the theoretical potential for low and medium temperature processes cannot be used because of mentioned restrictions. Although this assumption cannot be fully verified, it is also considered for this study, as the described reasons support that major restrictions exist for the use of solar heat for industrial processes.

A solar fraction is documented for six solar process heat systems in Germany. Three systems provide heat for surface treatment and electroplating, two in Food and beverages and one in a paint shop. The average solar fraction of these systems is 32% [20]. Within [4] 25 systems were dimensioned for case studies and suggested to participating companies. The average solar fraction of these systems was 29%. Six further case studies were done in [5] with an average solar fraction of 40%. Furthermore, for the potential study for the Netherlands [7] a solar fraction of 30% was assumed. Therefore, an average solar fraction of 30% was assumed in this study to determine the technical potential. Applying the figures for efficiency measures, restricted roof area and average solar fraction to the theoretical potential of 134 TWh per year, the technical potential for solar heat in industry in Germany can be estimated to 16 TWh per year or 3.4% of the total industrial heat demand.

As the heat demand presented in Tables 1 and 2 was verified with figures from official statistics and the references given in Section 3 support the temperature distribution, it can be concluded that the theoretical potential represents a reliable figure. In order to estimate the technical potential, a reduction of the theoretical potential due to possible efficiency measures and an average solar fraction were assumed. Both figures incorporate an uncertainty, the higher being in the reduction for efficiency measures and available roof area, as the assumption of the solar fraction is justified by several references. A reduced or increased value for efficiency measures and available roof area to 50% or 70% would lead to a technical potential of 20 or 12 TWh per year, respectively. This variation shows that the technical potential represents rather an estimate than a definite figure.

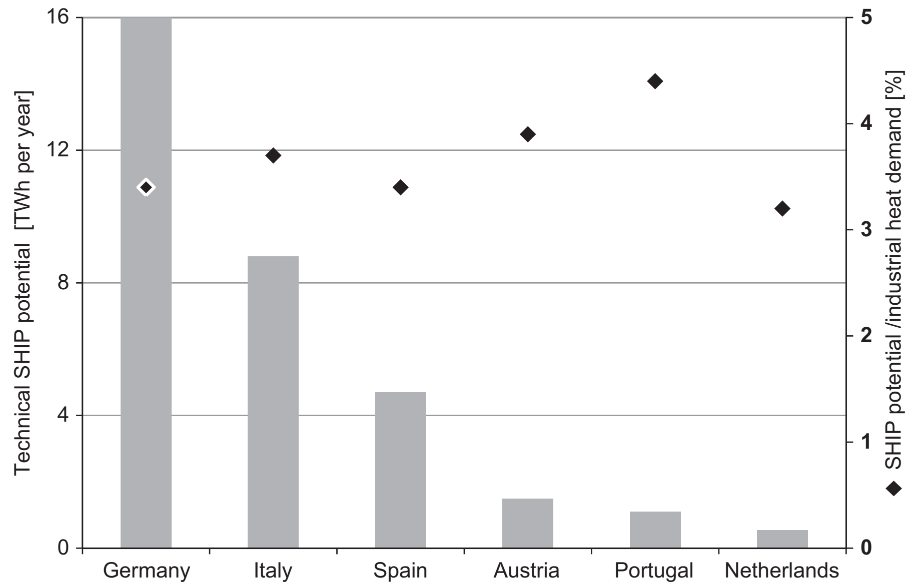

Fig. 3. Technical potential for solar heat for industrial processes in European countries.

In order to compare the estimated potential with prior potential studies, Fig. 3 shows, the technical potential for Austria [5], Italy [3], the Netherlands [7], Portugal and Spain [4]. As the figure shows, it is in a range between 3 and 4.5% of the industrial heat demand in the particular region and about 16.7 TWh per year for these five countries in total [3]. For the European Union (EU25) a potential of 72 TWh per year or 3.8% of the industrial heat demand in the EU25 is given in [3]. The calculated potential for Germany is within the range of prior studies, although additional industrial sectors were considered in this study. On the one hand this is can be explained by a lower solar fraction compared to e.g., [5]. On the other hand, the additional sectors only have a very small share of the overall heat demand.

The absolute number of 16 TWh per year represents by far the highest potential of solar heat for industrial processes in European countries, as shown in Fig. 3. Solar thermal collectors with about 25 GW_{th} (35 Mio. m^2) would be necessary to develop the technical potential, assuming an average annual solar system yield of 450 kWh/(m^{2*}a). For the EU25 in total about 110 GWth (155 Mio. m^2) would be needed which represents a substantial market for solar thermal systems.

5. Promising industrial sectors and processes

Within this section the most promising sectors for the use of solar heat are selected. Further, selected sectors are analyzed and suitable processes are identified.

5.1. Promising industrial sectors

A first selection of promising sectors was done by considering their heat demand below 300 °C, as Fig. 4 shows. Of the sectors of Table 2, six sectors with a heat demand below 300 °C of less than 2 TWh were excluded. Although Furniture and other goods has nearly the same heat demand below 300 °C than Wood, this sector summarizes many different sub-sectors and was therefore excluded. In a second step, the sectors of Basic metals and Non-metallic mineral products were excluded because of their high waste heat potential.

Fig. 4 indicates that the selected sectors represent a substantial share of the industrial heat demand. In total, theses 11 sectors consume about 88% of the industrial heat demand below 300 °C in Germany, including space heating and hot water.

Prior potential studies that were performed in the past for different countries or regions, identify several industrial sectors and processes as suitable for the application of solar thermal systems. Besides the studies for Austria [5], and Spain and Portugal [4], which are described in Section 2, further potential studies are available for Victoria (Australia) [6], Italy [3], the Netherlands [7], Sweden [8], and for Greece, Wallonia (Belgium) and a few industrial sectors in Germany [10]. Table 3 summarizes the sectors referred to as suitable in prior studies.

The relevance of individual sectors and therefore the temperature levels of the industrial heat demand can vary strongly in different countries. Nevertheless, the needed temperatures and processes within a sector and thus the promising sectors are transferable because production processes can be assumed to be similar across different countries. Therefore, the results of the prior studies support the selection of promising sectors for Germany. In the following selected sectors are analyzed and suitable processes for the integration of solar heat are identified. The sectors of Motor vehicles, Machinery and equipment and Electrical equipment are not covered, as a large share of its heat demand is for space heating and DHW and suitable processes are very similar to Fabricated metal. The sector of Printing is not analyzed in detail as one major process, which is drying of paper just below 200 °C, uses heat in this sector. The selection of sectors is based on the heat demand below 300 °C and its waste heat potential. More investigations, e.g., case studies, are necessary regarding the possible use of waste heat especially in the sectors of Motor vehicles, Fabricated metal, Machinery and equipment but also in Chemicals as they all have a certain high temperature heat demand. The question arises if high temperatures are needed at the same production sites as low temperature processes. The results of prior studies also show that some sectors are mentioned as suitable only in a few or a single study, which shows the need for further investigations.

The sector of **Chemicals and chemical products** has the highest quantitative potential for the application of solar heat because of its large heat demand. Although a large share of the heat is needed at high temperatures, there is still a considerable heat demand at low (<100 °C) and medium (<300 °C) temperatures. The sector has a share of 24% of the heat demand of the 11

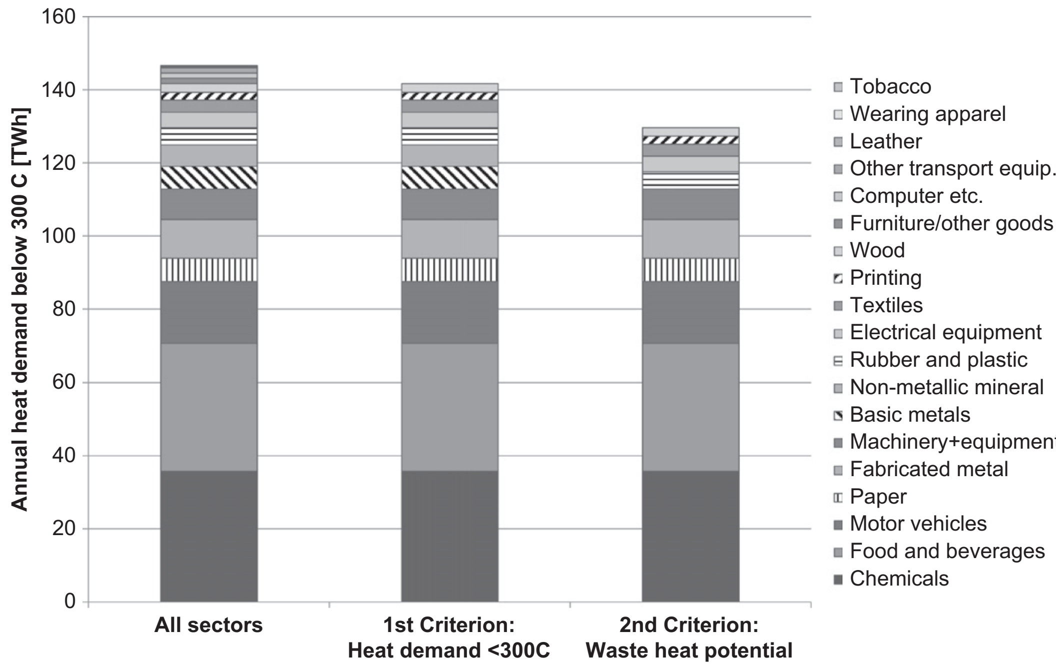

Fig. 4. Heat demand below 300 °C of all and the selected promising sectors.

Table 3
Suitable sectors mentioned in prior potential studies in the field of solar heat for industrial processes.

Industrial sector	Austria	Greece	Germany	Italy	Iberian Peninsula	Netherlands	Victoria (Australia)	Wallonia (Belgiun)
Chemicals and chemical products	X	X	–	X	X	–	X	X
Food products and beverages	X	X	X	X	X	X	X	X
Paper and paper products	–	X	X	X	X	X	X	X
Motor vehicles	–	X	X	X	X	–	–	–
Machinery and equipment	–	–	–	–	–	–	X	–
Rubber and plastic products	X	–	–	–	–	–	–	–
Textiles and textile products	X	X	–	X	X	X	X	X
Prefabricated concrete components	X	–	–	–	–	–	–	–
Tobacco products	–	X	–	X	X	–	–	X
Leather and leather products	–	X	–	X	X	–	–	–

selected sectors at temperatures below 100 °C. At medium temperatures (100 to 300 °C) the share is 36%. The average energy costs are in the range of 4% to 5% of the total manufacturing costs, which shows the importance of energy usage, but depend strongly on the subsector [21]. Especially the production of ammonia and petrochemicals, e.g., the production of polypropylene, are very energy intensive, whereas the subsector of pharmaceutical needs less energy. Potential processes for the integration of solar heat are cooking at temperatures of 85 to 110 °C, distillation (110 to 300 °C), bio-chemical processes at low temperatures (< 60 °C), preheating and polymerization processes [22]. Due to very complex production facilities and the possible use of waste heat a deeper analysis of this sector is necessary to identify the most suitable application areas for solar heat.

The sector of **Food products and beverages** is mentioned as suitable in all prior potential studies. It has about the same shares of the heat demand at low and medium temperatures of the promising sectors as Chemcials. Within Food products and beverages, the major share of the heat is needed at low temperatures below 100 °C, accounting for 58%. Additional 42% are consumed between 100 and 300 °C. Due to the fact, that no consistent data of the heat demand of the subsectors is available, data for the overall energy demand was considered here to identify the most promising subsectors [23]. Although the sugar industry has the highest share of the energy demand, the potential is limited, because production takes place mainly in autumn and winter, and combined heat and power is used extensively. Milk production, slaughtering and meat production, and fruits and vegetables have a considerable heat demand and therefore seem promising for the use of solar heat. Further subsectors which appear suitable are beer production, mineral water, feed and malt. Common processes are pasteurization of liquid goods at 65 to 100 °C, cooking at 100 °C in meat processing, blanching of vegetables or meat (65 to 95 °C), drying and evaporation at 40 to 130 °C in fruit and vegetable processing and cleaning of products and production facilities in all subsectors at 60 to 90 °C.

The sector of **Paper and paper products** has a share of 12% of the heat demand below 300 °C of the selected sectors. Within paper industry about two-thirds of the heat demand is needed at temperatures between 100 and 500 °C, mainly for drying processes. Still, one-third of the heat demand is consumed at temperatures below 100 °C. The temperature distribution of Table 2 shows a high heat demand at temperatures between 100 and 200 °C and 300 and 500 °C. Drying is the process with far the highest energy consumption in paper production. Drying cylinders using steam at temperatures of 130 to 200 °C are widely used. Further, directly fired drying hoods, operating at around 400 °C, are frequently installed in tissue production (hygiene

paper). The average share of energy costs is about 11% of total manufacturing costs and can sometimes reach up to 25% [24]. This shows the high importance of energy efficiency and the utilization of renewable energy in this sector. Besides drying, de-inking of recycled paper preheating of boiler feed water represents a promising application for solar thermal energy in this industry sector. Further suitable processes are cooking and bleaching.

The sector of **Fabricated metal products** has a share of 8% of the heat demand below 300 °C of the selected sectors. Low temperature heat below 100 °C, including process heat, space heating and hot water accounts for 64% of the total heat demand. Still, processes at temperatures higher than 300 °C also account for 28% of the heat demand. According to [25] energy costs are only 0.3% to 1.6% of the total manufacturing costs within the sector. Especially for coating processes the required heat is at low temperatures. For example, the processes degreasing, electroplating and pickling all require temperatures below 100 °C. Air-drying is a common process that requires hot air with about 120 °C. Similar processes can be found in the sectors of Motor vehicles, Machinery and equipment, and Electrical equipment.

Of the heat needed in **Rubber and plastic products** 43% is at temperatures below 100 °C and 40% at 100 to 300 °C. According to [1] the share of energy costs is 3%. Besides the supply of hot water and space heating, drying of plastic pellets is a potential process for solar thermal energy. The pellets are air-dried at temperatures from 50 to 150 °C to ensure quality. Another possible application is preheating of pellets before processing e.g., by extrusion or injection molding.

Manufacturing of **Textiles** consumes 4% of heat demand below 300 °C of the 11 selected sectors. The heat demand is mainly limited to temperatures below 100 °C. In contrast to the numbers of Table 1, the analysis showed that single processes with temperatures higher than 100 °C exist in this sector. Within the textile industry washing at 40 to 90 °C, drying, and a large number of finishing processes like bleaching at 70 to 100 °C, desizing at 80 to 90 °C and coloring at 40 to 120 °C are the main consumers of process heat. At a rough estimate up to 25% to 50% [5] of heat needed in the Textiles sector could be covered by solar thermal energy. This represents a considerable potential, although the sectors share of the industrial heat demand is quite low.

The **Wood** sector consumes only 2% heat demand below 300 °C of the 11 selected sectors. The most important subsectors regarding energy and heat consumption are the manufacture of (veneer-) plywood and lumber mills. A large part of the heat demand (82%) is needed at temperatures below 100 °C. Drying of raw wood before processing represents the most important process for the integration of solar heat. Besides this, processes like steaming, cooking and pickling are promising due to low or moderate temperatures.

The potential for individual sectors is important to judge which sectors are most promising for the application of solar heat. Fig. 5 shows the technical potential of the 11 selected sectors, which was determined in the same way as the overall potential in Section 4.

Besides the calculated potential, the temperature distribution for each individual sector is visible in Fig. 4, which is important to judge about the most promising sectors. For Motor vehicles, Fabricated metal, Machinery and equipment, and Electrical equipment a large share of the potential is heat demand for space heating and DHW. Chemicals and Food and beverages have by far the highest potential of all sectors, whereas the integration of solar heat processes Food and beverages seems easier due to lower complexity of the production processes and therefore offers the higher short-term potential, as [26] states.

5.2. Promising industrial processes

The analysis of industrial sectors shows, that various processes are suitable for the use of solar heat. Fig. 6 shows an overview of the process identified as suitable for the integration of solar heat in this study, as they all take place at low or medium temperatures. The selection of processes was verified with other studies [4,5,10]. As the figure shows, various processes suitable for the use of solar heat can be found in several of the selected sectors.

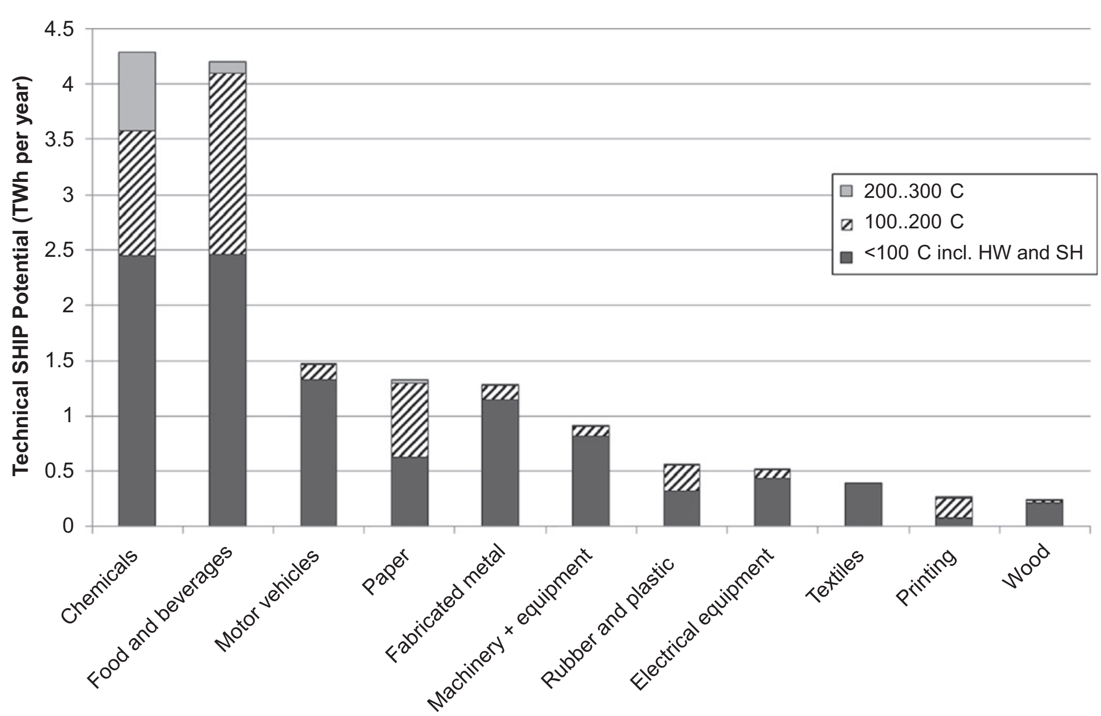

Fig. 5. Technical potential of the nine selected sectors divided in temperature ranges.

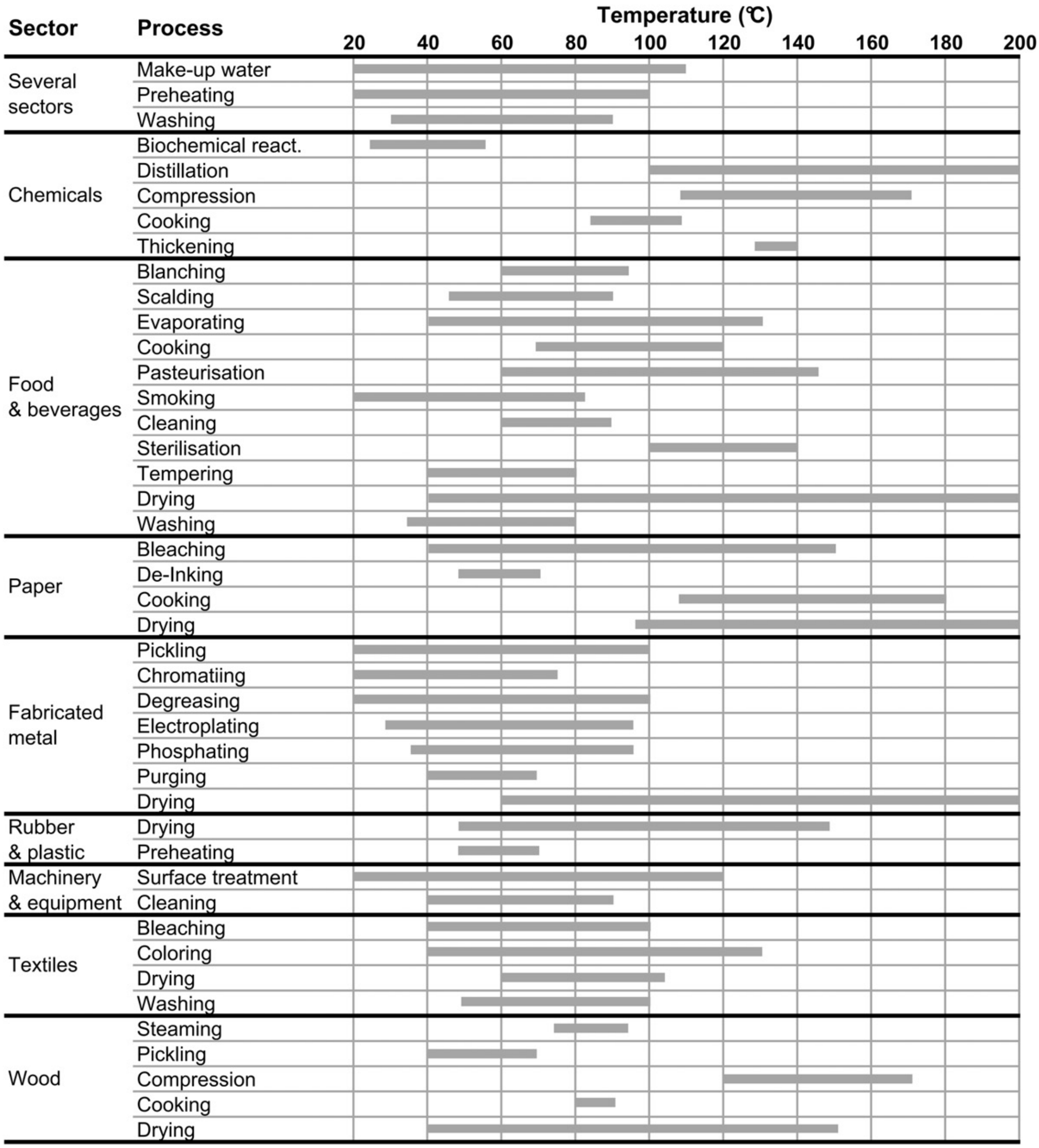

Fig. 6. Promising processes for the integration of solar heat identified in this study and verified with [4,5,10].

6. Conclusions

At first, this paper analyzed the temperature distribution of the industrial heat demand in Germany. An overview of the heat demand below 300 °C in Germany is presented, which is crucial to judge about the potential, not only of solar thermal, but also CHP and heat pumps in industry. The analysis showed that the most important temperature ranges for the application of solar process heat in Germany are below 100 °C and between 100 and 200 °C. Further collector developments should focus on cost reduction for standard collectors used below 100 °C and development of cost effective process heat collectors up to 200 °C as well as demonstration projects. Steam production on supply level of an industrial enterprise is a promising application for solar process heat as the effort for integration can be reduced compared to integration on process level. As nearly all steam networks are operated at pressures corresponding to temperatures lower than 200 °C, this temperature range should be a major focus for future developments. As a high share of the low temperature heat demand is for space heating, the combination of solar thermal systems with combined heat and power and heat pumps needs to be investigated.

A theoretical potential of solar heat for industrial processes in Germany of 134 TWh per year, and a technical potential of 16 TWh per year were determined. In future, the experience of additional solar thermal systems in industry will help to achieve more reliable figures, e.g., efficiency measures and solar fraction, to estimate the technical potential. The share of the theoretical potential which can technically be developed, and to a certain extend also the theoretical potential itself, always depend on the available and feasible solar thermal technology. Still, it can be concluded that a substantial technical potential for the use of

solar heat, and therefore a good possibility to reduce greenhouse gas emissions, exists in Germany. Nevertheless, increased efficiency of high temperature processes is crucial to lower the greenhouse gas emissions of industry substantially.

Finally, the most promising industrial sectors were identified and analyzed regarding suitable processes. Some of the selected sectors surely offer broad possibilities for the use of solar heat, whereas in others the restrictions of energy efficiency might reduce the theoretical potential substantially. The sectors of Chemicals and Food and beverages have the highest potential for the use of solar heat. In Chemicals the possibilities for the use of waste heat have to be investigated in more detail, since a large amount of heat is consumed at temperatures above 500 °C. Considering its big share of the industrial heat demand at low temperatures, the results of the prior studies and the variety of suitable processes, the sector of Food and beverages has the highest short-term potential for the use of solar thermal energy in industry.

Acknowledgement

The authors gratefully acknowledge the financial support provided by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, contract No. 0329601T.

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